

AN INVESTIGATION OF THE
EARLY STAGES OF FRETTING

William F. Tighe, Jr.

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AN INVESTIGATION OF THE EARLY STAGES OF FRETTING

by

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TIGHE

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THESIS

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EMENTS FOR THE

NAVAL ENGINEER

at the

INSTITUTE OF TECHNOLOGY

, 1954

Letter on front cover:

AN INVESTIGATION OF THE EARLY
STAGES OF FRETTING

WILLIAM F. TIGHE, JR.

ABSTRACT

Title: AN INVESTIGATION OF THE EARLY STAGES OF FRETTING

Author: William F. Tigue, Jr., Lieutenant, U.S. Coast Guard

Submitted to the Department of Naval Architecture and Marine Engineering on May 22, 1934, in partial fulfillment of the requirements for the degree of Naval Engineer.

The primary purpose of this investigation was to determine the shape of the initial portion of the curve of fretting weight loss versus the number of cycles run. Previous work in the field has shown this curve to be concave downward over the initial portion. It has been proposed that the curve is actually concave upward over this portion, due to the fact that the abrasive action is presumably more violent than the shearing action. The conditions under which the tests were conducted, were chosen such that it was anticipated that the specimen weight loss would be relatively large over a short interval of time. The tests of mild steel specimens fretted against mild steel specimens were conducted under these conditions, varying the duration of test from 1 to 10,000 cycles.

The results of this investigation showed that the curve in question actually had a point of inflection in the portion under investigation. At the origin, the curve was concave downward followed by a turn to concave upward. This result not only substantiated the initial proposal but also added some additional information which was not anticipated.

It is recommended that these tests be repeated in dry air as well as other atmospheres to establish definite quantitative results. It is also recommended that the frequency of alternation be lowered to as small a value as possible in order to increase the specimen weight loss in a given interval of time.

The second purpose of the investigation was to establish a relationship between specimen weight loss and some physical measurement of fretting damage. To this end, the area of damage as well as its depth was measured and plotted against specimen weight loss.

The result of this series of investigations showed that any attempt to use the area of damage as a substitute for weight loss is impractical. It appears to be quite possible to use the depth of damage as a measure of fretting damage. The relationship obtained between specimen weight loss and the depth of fretting damage can be considered qualitative only due to a lack of sufficient data. The depth of damage, however, definitely increases as the weight loss increases. It is recommended that additional tests be made to firmly establish the quantitative relationship between specimen weight loss and the depth of fretting damage.

Thesis Supervisor: I-Ming Peng, Ph.D.

Title: Assistant Professor of Mechanical Engineering

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TRANSIT

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Technology

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RECEIVED: OFFICE: TIGHE, WILLIAM F.

TITLE: An Investigation of the Early Stages of Fretting,

Submission Date: Massachusetts Institute of Technology, 1954

Classification Code: Thesis 1954 Massachusetts Institute of

Technology.

1954.

Cambridge, Massachusetts

Subject: Naval Architecture May 22, 1954

Title

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1954.

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Secretary of the Faculty
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Dear Sir:

In accordance with the requirements for the Degree
of Naval Engineer, I submit herewith a thesis entitled,
"An Investigation of the Early Stages of Fretting."

Respectfully,

William F. Tighe, Jr.
Lieutenant
U. S. Coast Guard

University of the Pacific
Department of Education
Stockton, California

Dear Sir:

In accordance with the requirements for the degree of Master of Science, I hereby certify that I have completed the requirements for the degree of Master of Science in the Department of Education, University of California, Los Angeles, California.

Sincerely,
[Signature]

WILLIAM T. WILSON
JANUARY 1, 1900
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19110 10 INVESTIGATION OF LOW MILEAGE EFFECTS OF ELECTRICITY

PUBLISHED IN 1954: ACKNOWLEDGEMENTS INVESTIGATION OF TECHNOLOGY, 1954:

INVESTIGATION 1954: UNDER THE INVESTIGATION INSTITUTE OF

TECHNOLOGY.

1954:

19110 10 INVESTIGATION OF LOW MILEAGE EFFECTS

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The author wishes to express his sincere

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thanks and appreciation to Professor I-Ming Feng

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for his advice and encouragement during this

19110

investigation. Appreciation is also extended

to Mr. J. Purdy for his help in setting up the

testing equipment.

RECOMMENDATIONS

The action which is expressed in the above
findings and recommendations to Professor I. H. Hall
for his advice and assistance during this
investigation. Information is also extended
to H. J. Hall for his help in setting up the
testing equipment.

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I INTRODUCTION

Fretting is a type of damage that occurs at the interface of two loaded surfaces that are in contact and subject to relative slip. Fretting often appears on surfaces intended to have no relative motion but which are associated with vibrating machinery. It may occur, for example, on the mating surfaces of a bearing race and of a shaft tightly fitted together. It has been shown that some slippage, no matter how small, is necessary to cause fretting. In the absence of slip there is no fretting (3, 8).

Fretting damage is a continual source of uncertainty in the operation of all machinery subject to vibration, as it quickly destroys close tolerances and increases the susceptibility to fatigue (4). Examples of fretting damage are often found in variable-pitch propellers, connecting rods, knuckle pins, ball and roller bearings, clamped and bolted flanges, pins in gear trains, suspension springs, electrical contacts, and splined surfaces. This type of damage is particularly serious in the airplane and automotive industries where close fits are employed on equipment subject to vibration. In order to eliminate or mitigate the damage caused by fretting, a better understanding of the subject is essential. The purpose of the present investigation is to add to the understanding of the subject of fretting and the means of investigating fretting damage.

1. INTRODUCTION

Fracture is a type of damage that occurs in the interface of two loaded members that are in contact and subject to relative slip. Friction often appears on surfaces intended to have no relative motion but which are associated with vibrating machinery. In any case, the members, on the mating surfaces of a bearing race and of a shaft, are rigidly fitted together. It has been shown that even slight, no matter how small, is necessary to cause fracturing. In the absence of slip there is no fracturing (1, 2).

Fracture damage is a mechanical source of uncertainty in the operation of all machinery subject to vibration, as it directly changes those parameters and properties the susceptibility to fatigue (3). Examples of fracturing damage are often found in variable-stress systems, connecting rods, torsion bars, ball and roller bearings, shafts and helical gears, pins in gear trains, expansion joints, electrical contacts, and optical surfaces.

This type of damage is particularly serious in two respects and extensive literature exists that are devoted to equipment subject to vibration. In order to eliminate or minimize the damage caused by fracturing, a better understanding of the subject is essential.

The purpose of the present investigation is to aid in the understanding of the subject of fracturing and the means of investigating fracturing damage.

The majority of the work done to date in the field of fretting has dealt with the mechanism of fretting and some of its qualitative aspects. Feng (2, 9, 10) has analyzed the basic factors of metal transfer and wear. The mechanism of wear, as proposed by Feng, is caused by a pair of actually contacting high spots. When these contacting high spots support a normal load that is large enough to cause plastic deformation of the metal, the deformation will cause a roughening of the interface. This roughening of the interface produces a mechanical interlocking which strengthens the interface in resisting a tangential force. Thus the application of a tangential force will cause the peak of one of the pair of high spots to shear off instead of separating the contacting high spots at the original interface. This sheared peak may either become a loose wear particle or remain attached, depending upon the factors operating to cause it to adhere to the adjacent high spot. Feng and Rightmire (1) have applied this theory to explain the mechanism of fretting, and have shown mechanical wear to be the primary cause of fretting damage.

The wear particles formed by the shearing off of the peaks of the contacting high spots form hard oxides which cause abrasive wear. A number of investigations (1, 3, 8, 10) have been made in different atmospheres to determine the effect of oxides on fretting damage. These investigations have shown that oxidation, while having a very marked effect, is only a secondary cause of fretting.

The majority of the work done to date in the field of freezing has dealt with the mechanism of freezing and some of the qualitative aspects. Few (1, 2, 10) have assigned the basic theory of metal freezing and some. The mechanism of water, as proposed by Lang, is caused by a pair of mutually neutralizing ions, which then combine to form a neutral pair and a neutral ion pair is later formed in some specific direction of the metal, the deformation will cause a reorganization of the molecules. This reorganization of the molecules produces a mechanical deformation which strengthens the lattice to resist a longitudinal force. Thus the application of a longitudinal force will cause the break of one of the pair of ions to break off instead of separating the combination of ions at the critical direction. This should break up other bonds a lower rate particle or several atoms, depending upon the force applied to cause it to break to the minimum high spot. Few and Lang (1) have applied this theory to explain the mechanism of freezing, and have shown experimentally that to be the primary cause of freezing damage.

The new technique found by the changing all of the bonds of the combination ions from just a pair which cause a reorganization. A number of investigations (1, 2, 3, 4, 10) have been made to attempt to determine the effect of various on freezing damage. These investigations have shown that crystalline, while having a very marked effect, is with a secondary cause of freezing.

In addition to the investigations of the effect of atmospheres, investigations have been made of some of the other factors affecting fretting damage. Tests conducted by Feng and Uhlig (8) have shown that a decrease in fretting damage is caused by an increase in relative humidity, temperature and frequency of alternation; and an increase in fretting damage is caused by an increase in the number of cycles run, relative slip and normal load. Parts of these tests have also been corroborated by previous investigators (1,3). In addition, fretting damage appears to be greater, other things being equal, the better the original fit of the mating surfaces (6).

Several investigations have been made of fretting damage using various metals and nonmetals fretted against themselves and against each other. Godfrey (7) used platinum, glass, quartz, ruby, mica, and chrome-alloy steel. He found that the tendency for fretting depended upon the surface hardness of the metal tested. He also found that the introduction of a lubricant between the surfaces of the materials decreased the amount of fretting damage done in all cases, but that it was not eliminated. This latter fact was also borne out in the investigations of Tomlinson, Thorpe and Gough (3).

References (1) and (8) both present the results of mild steel specimens fretted against mild steel specimens in dry air. These results are presented in the form of curves of Specimen Weight Loss versus Number of Cycles Run. Both of these curves are concave downward at the origin, i.e., during the shifting period from shearing

In addition to the investigation of the effect of temperature, investigations have been made of some of the other factors affecting freezing damage. These conducted by King and Little (8) have shown that a decrease in freezing damage is caused by an increase in relative humidity, temperature and duration of immersion; and an increase in freezing damage is caused by an increase in the number of cycles, relative air and water loss. Tests of these factors have also been conducted by previous investigators (1,2). In addition, freezing damage appears to be greater, other things being equal, the better the original fit of the mating surfaces (6). General investigations have been made of freezing damage using various metals and nonmetals tested against themselves and against each other. Bailey (7) used platinum, glass, quartz, ruby, mica, and aluminum-oxide sheets. He found that the tendency for freezing depended upon the surface hardness of the metal tested. He also found that the incidence of a fracture between the surfaces of two materials depended on the amount of freezing damage done in all cases, but that it was not eliminated. This latter fact was also borne out in the investigation of Tullman, Thompson and Smith (3). Tullman (1) and (2) both present the results of which show specimens tested against each other appeared on the air. These results are presented in the form of curves of specimen weight loss versus thickness of specimen. Tests of these curves are shown in diagram of the weight loss during the freezing period from cooling

action to abrasive wear. Feng and Rightmire (1) have proposed that this curve is actually concave upward during the shifting period. This proposal is based on the fact that the rate of wear probably increases during the shifting period as the abrasive action is presumably more violent than the shearing action. This proposal seems to be supported by the points plotted in Figures 5 and 6 of the investigation by Wright (11). One of the purposes of the present investigation is to substantiate this proposal by decreasing the number of cycles run and increasing the amount of fretting that occurs by decreasing the frequency of alternation. This will tend to expand the initial portion of the curve. The test apparatus shown in Figures I, II, and III and described in Appendix A was used for the investigation.

Using weight loss as a measure of fretting damage is not always the best means, even though it can be measured quantitatively and relatively accurately. An excellent example is the case in which two clean surfaces are fretted against each other in a vacuum. Because of the adhesion between clean metallic surfaces in a vacuum, the peak sheared from one high spot sticks to the opponent high spot and becomes a piece of transferred metal. Thus very little loose wear material can be produced, metal merely being transferred back and forth from one specimen to another. If the specimens are made of the same material, the weight loss of each is practically nil.

action to determine what. (1) That proposed that
 this curve is actually constant around during the existing period.
 This proposed is based on the fact that the rate of new production
 increases during the existing period as the domestic nation is
 increasingly more victim than the foreign nation. This proposed
 seems to be supported by the notes placed in Figures 2 and 3 of
 the investigation by White (11). One of the purposes of the present
 investigation is to substantiate this proposed by determining the
 number of operations and determining the amount of trading that
 occurs by determining the frequency of circulation. This will tend
 to extend the initial portion of the curve. The first operation seems
 to require 1, 2, and 3 and should be repeated as a series of
 the investigation. The investigation seems to require 1, 2, and 3
 and should be repeated as a series of trading periods to test
 the first curve, even though it can be somewhat qualitatively
 and relatively accurate. An excellent example is the case in which
 two lines intersect and the first curve is a curve in a curve.
 Because of the relation between these relative systems in a system,
 the first curve is not the first curve in the system but the
 and because a shape is determined. The very little is
 very detailed and is somewhat, and every being determined each
 and the two are operations in another. If the operations are made
 of the new system, the weight loss of each is practically nil.

Nevertheless, both specimens are subject to serious damage caused
[1]
by metal transfer. A second purpose of this investigation is
to try and establish a technique for measuring the damage in such
cases by correlating weight loss and some physical measure of
fretting damage. An attempt will be made to find some relationship
between specimen weight loss and either the depth or the area of
damage or both.

[1] Feng, I. Ming, and Rightmire, B.G., "The Mechanism of Fretting",
Lubrication Engineering, Vol. 9, No. 3, 1953, p. 135.

Government, both business and subject to certain laws and

by itself. (1) A second purpose of this investigation is

to try and establish a technique for recording the human in man

of course by observation which has been and some physical means of

recording human. In attempt will be made to find some relationship

between physical and mental and either the degree of the level of

degree of body.

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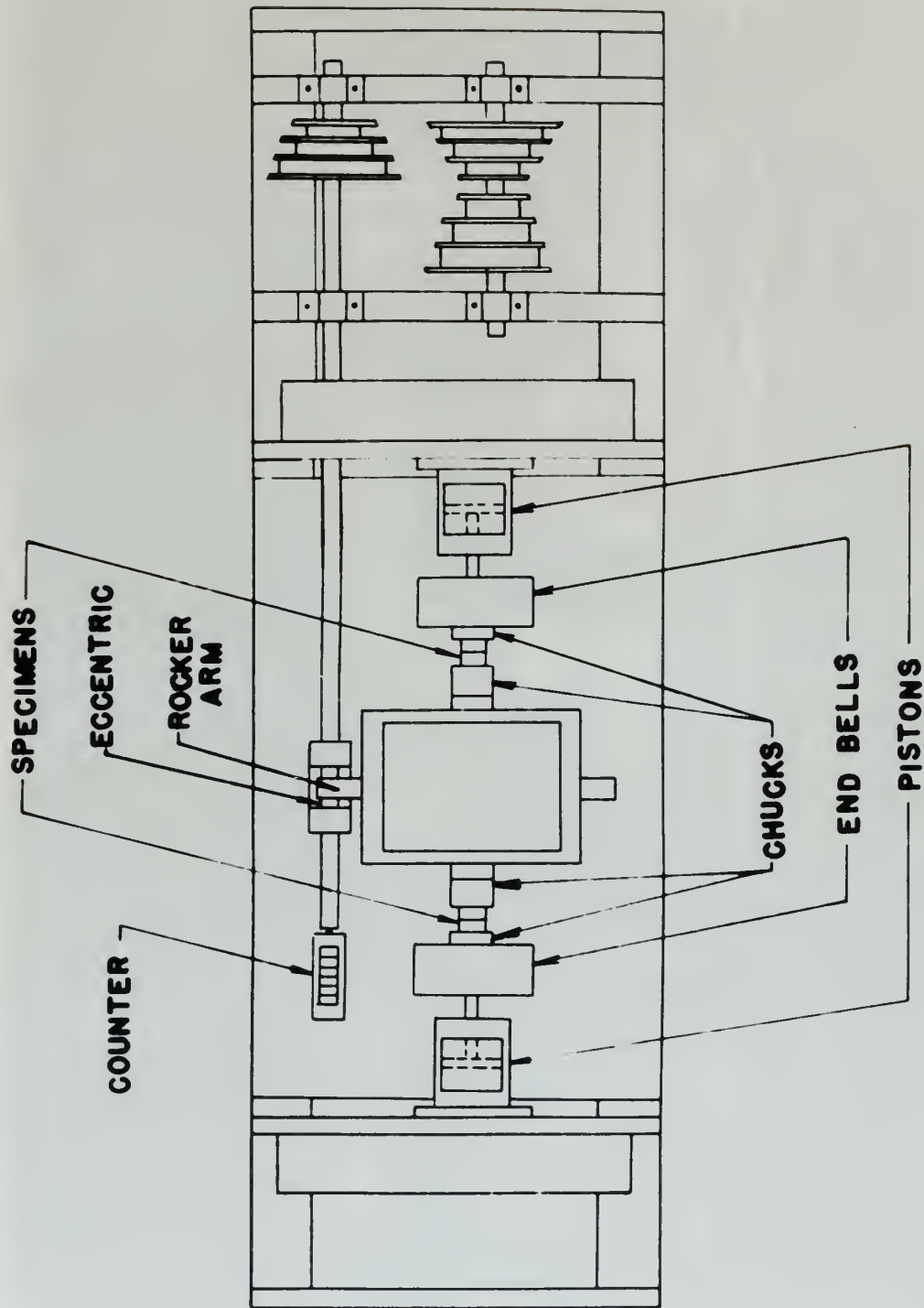
and physical means of recording the human in man

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11) The first purpose of this investigation is to try and establish a technique for recording the human in man of course by observation which has been and some physical means of recording human. In attempt will be made to find some relationship between physical and mental and either the degree of the level of degree of body.



SCHEMATIC OF TEST MACHINE

FIGURE 1

FIGURE II
Top view of test apparatus

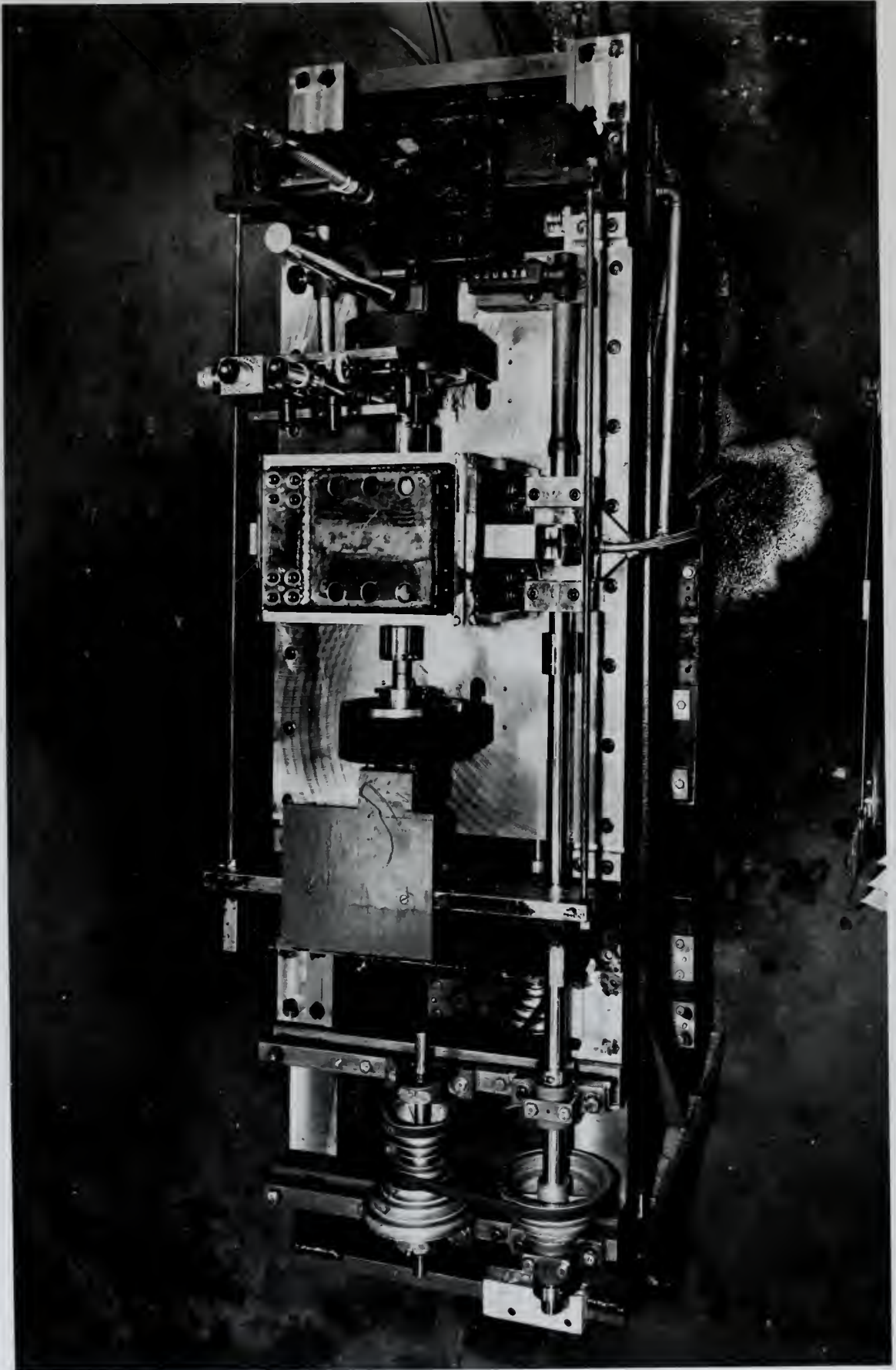


FIGURE III
Side view of test apparatus

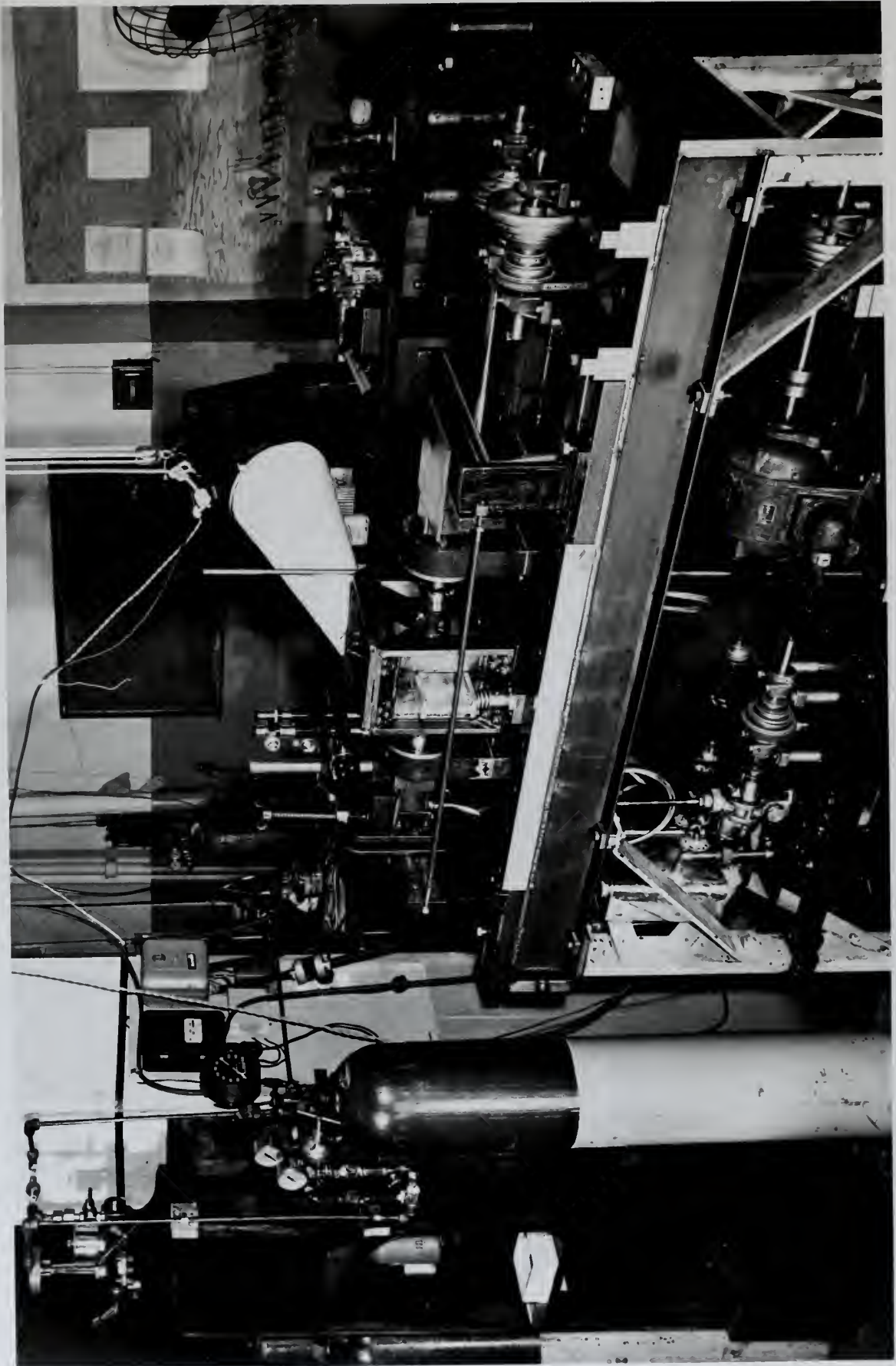
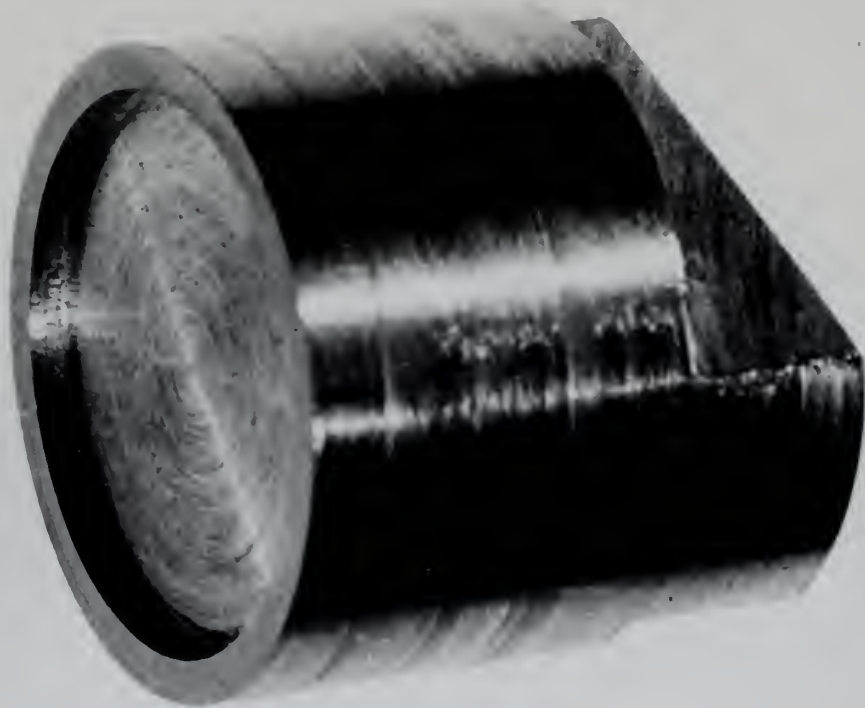


FIGURE IV
Standard test specimen



II PROCEDURE

The specimens to be tested were prepared as outlined in Appendix B, mounted in the test machine and the tests made. All of the tests were made under a standard set of test conditions in an atmosphere of dry air at room temperature. The standard normal loading was 5300 psi. The relative slip was maintained at 0.0036 inch, and the frequency of alternation was kept constant at 79 cycles per minute.

Several tests were first made to determine an appropriate number of cycles at which the fretting damage was such that it was fairly easy to identify individual pits. Two runs were then made, one for five cycles duration and one for ten cycles duration. A number of individual pits were selected from each specimen and a measurement made of each pit area and its depth. This procedure was followed in order to find a relationship between pit area and depth indicating pit growth. It was anticipated that this might lead to a relationship that could be correlated with specimen weight loss.

Several tests were then made varying the duration of test from 10 to 300 cycles. The specimens were pickled once and weighed upon the completion of each test. The recorded specimen weight loss was an average of the weight losses for the four specimens tested. A representative specimen from each of six tests was selected, and

II. Procedure

The procedure for the tests was as follows:

1. The test was conducted in the test machine and the test made.

2. All of the tests were made under a standard set of test conditions.

3. The atmosphere of the air at room temperature. The standard

humidity was 50%. The relative humidity was maintained

at 0.005 inch, and the frequency of observation was kept

constant at 10 cycles per minute.

4. Several tests were first made to determine an appropriate

number of cycles at which the frequency changes were made. It

was fairly easy to identify individual plate. The tests were then

made, one for five cycles duration and one for ten cycles duration.

5. A number of individual plate were selected from each specimen and a

measurement made of each plate and the depth. This procedure

was followed in order to find a relationship between plate area and

depth indicating its growth. It was anticipated that this might

lead to a relationship that could be correlated with specimen weight

loss.

6. Several tests were then made varying the duration of test

from 10 to 500 cycles. The specimens were weighed once and weighed

again after the completion of each test. The recorded specimen weight loss

was an average of the weight losses for the four specimens tested.

7. A representative specimen from each of six tests was selected, and

a measurement was made of the total area of fretting damage and the greatest depth of damage. The purpose of this series of tests was to find the shape of the curve of specimen weight loss versus the number of cycles run. In addition to this, the tests were an attempt to find a relationship between total area and depth of damage and to corrolate this with specimen weight loss.

A series of tests was made varying the duration of test from 1 to 10,000 cycles. The specimens were cleaned and weighed after test, then pickled and reweighed. This was followed by a second pickling and reweighing. One or two specimens from each test were selected and a measurement made of the deepest depth of fretting damage. The purpose of this series of tests was three fold. First it was an attempt to determine the fretting weight loss curve. Secondly it was felt that this procedure would lead to a relationship between specimen weight loss and depth of damage. Thirdly it was an attempt to determine what effect a first and second pickling procedure would have upon specimen weight loss.

A preliminary test was made of the total mass of feeding larvae
 and the greatest depth of feeding. The purpose of this series of
 tests was to find out what the mass of feeding larvae was
 under the most of feeding. In addition to this, the tests
 were an attempt to find a relationship between feeding rate and
 depth of feeding and to determine what factors might limit
 feeding. A series of tests was made varying the duration of feeding
 from 1 to 10,000 hours. The specimens were observed and weighed after
 each, then killed and weighed. This was followed by a second
 feeding and weighing. One or two specimens from each test were
 selected and a comparison made of the depth of feeding
 between. The purpose of this series of tests was to find out what
 it was an attempt to determine the feeding rate and mass.
 Finally it was felt that this procedure would lead to a relation-
 ship between feeding rate and depth of feeding. This is
 the attempt to determine what effect a given feeding rate has on
 the depth of feeding.

III RESULTS

The results of the investigation are presented in Tables I, II, and III, and in figures V, VI, VII, and VIII. Significant points to be noted are as follows:

1. Initially the area of an individual pit increases faster than the depth. The depth then begins to increase faster than the area, followed by the area again increasing faster than the depth.
2. Initially the rate of specimen weight loss is high and soon reaches a steady state. Shortly after this steady state is reached, the rate of weight loss again increases markedly and settles at a new steady state value.
3. The specimen weight loss due to both first and second pickling is not a constant, but is a function of the amount of damage caused by fretting.
4. The total area of fretting damage is essentially a constant over the range from 30 to 300 cycles.
5. The specimen weight loss increases with an increase in the depth of fretting damage.

III. RESULTS

The results of the investigation are presented in Tables I, II, and III, and in Figures 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100.

to be noted are as follows:

1. Initially the rate of an individual oil lamp was lower than the rate of the lamp. The rate then began to increase faster than the rate, followed by the rate again increasing faster than the rate.
2. Initially the rate of a modern electric lamp is high and then decreases a steady rate. Shortly after this steady rate is reached, the rate of weight loss again increases steadily and remains at a new steady state value.
3. The modern electric lamp has two distinct and steady periods in its operation, but is a constant, but is a function of the amount of energy consumed by the lamp.
4. The total rate of weight loss in a modern electric lamp is constant over the range from 50 to 100 watts.
5. The modern electric lamp increases with an increase in the degree of oxidation.

TABLE IINDIVIDUAL PIT MEASUREMENT DATA

Normal Load - 5300 psi
Slip - 0.0036 in.

Medium - dry air

Pit	Duration of Test(cycles)	Frequency of Test (cpm)	Pit Area ($\times 10^{-6}$ in ²)	Pit Depth ($\times 10^{-4}$ in)
1	5	79	18.05	0.762
2	5	79	49.20	1.476
3	5	79	38.40	1.738
4	5	79	45.10	2.500
5	5	79	62.60	3.167
6	5	79	134.80	4.048
7	5	79	113.10	6.310
8	10	57	70.10	1.953
9	10	57	70.85	1.953
10	10	57	39.60	2.310
11	10	57	38.20	2.500
12	10	57	41.60	2.500
13	10	57	79.20	2.500
14	10	57	38.20	2.928
15	10	57	75.00	3.309
16	10	57	176.20	3.500
17	10	57	114.50	3.809
18	10	57	159.7	3.977

TABLE

OF THE PHYSICAL PROPERTIES OF THE

GASES

By J. H. VAN DER WOUDE
and J. H. VAN DER WOUDE

Temp. (°C.)	Specific Gravity (at 0°C.)	Boiling Point (°C.)	Freezing Point (°C.)	Triple Point (°C.)
1	0.00129	-182.96	-182.96	-182.96
2	0.00129	-182.96	-182.96	-182.96
3	0.00129	-182.96	-182.96	-182.96
4	0.00129	-182.96	-182.96	-182.96
5	0.00129	-182.96	-182.96	-182.96
6	0.00129	-182.96	-182.96	-182.96
7	0.00129	-182.96	-182.96	-182.96
8	0.00129	-182.96	-182.96	-182.96
9	0.00129	-182.96	-182.96	-182.96
10	0.00129	-182.96	-182.96	-182.96
11	0.00129	-182.96	-182.96	-182.96
12	0.00129	-182.96	-182.96	-182.96
13	0.00129	-182.96	-182.96	-182.96
14	0.00129	-182.96	-182.96	-182.96
15	0.00129	-182.96	-182.96	-182.96
16	0.00129	-182.96	-182.96	-182.96
17	0.00129	-182.96	-182.96	-182.96
18	0.00129	-182.96	-182.96	-182.96
19	0.00129	-182.96	-182.96	-182.96
20	0.00129	-182.96	-182.96	-182.96

TABLE II

TABULATED RESULTS

Medium - Dry air
Polish - No. 00 Emery/Paper

Load - 5300 psi
Slip - 0.0036
Frequency - 79 cpm

Number of cycles run	Weight loss after 1st pickling (mg) 4 specimen Average	Weight loss after 2nd pickling (mg) 2 specimen Average	Depth of Damage after 1st pickling ($\times 10^{-3}$ in.)	Area of Damage after 1st pickling (in^2)	Depth of Damage after 2nd pickling ($\times 10^{-3}$ in.)
10	0.825	1.0	1.60	-	-
20	1.088	-	-	-	-
20	0.800	1.0	-	-	-
30	0.610	-	3.064	0.0356	-
40	0.800	-	2.508	0.0413	-
50	1.150	-	2.104	0.0350	-
75	1.250	-	2.828	0.0425	-
125	1.000	1.20	-	-	2.17
150	1.000	-	2.710	0.0411	-
300	1.725	-	4.393	0.0436	-

TABLE III

TABULATED RESULTS

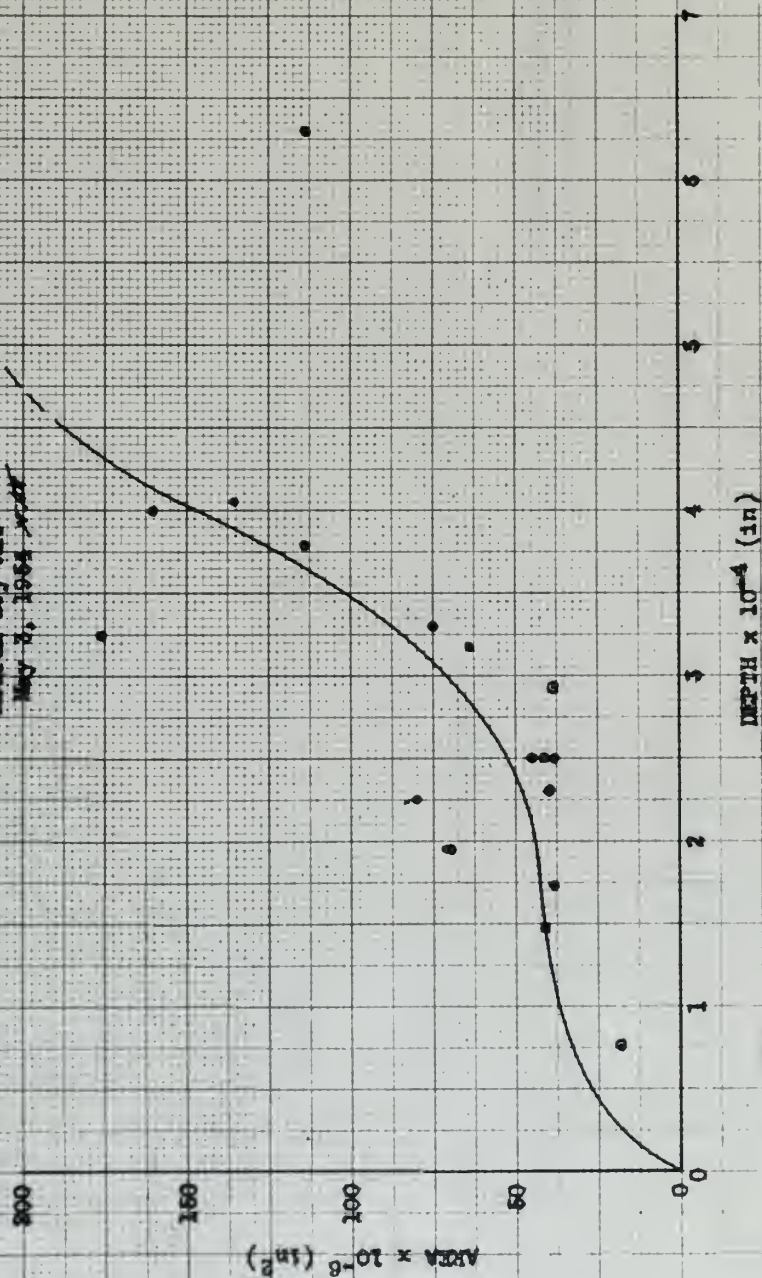
Load - 5300 psi
Slip - 0.0036 in.
Frequency - 79 cps

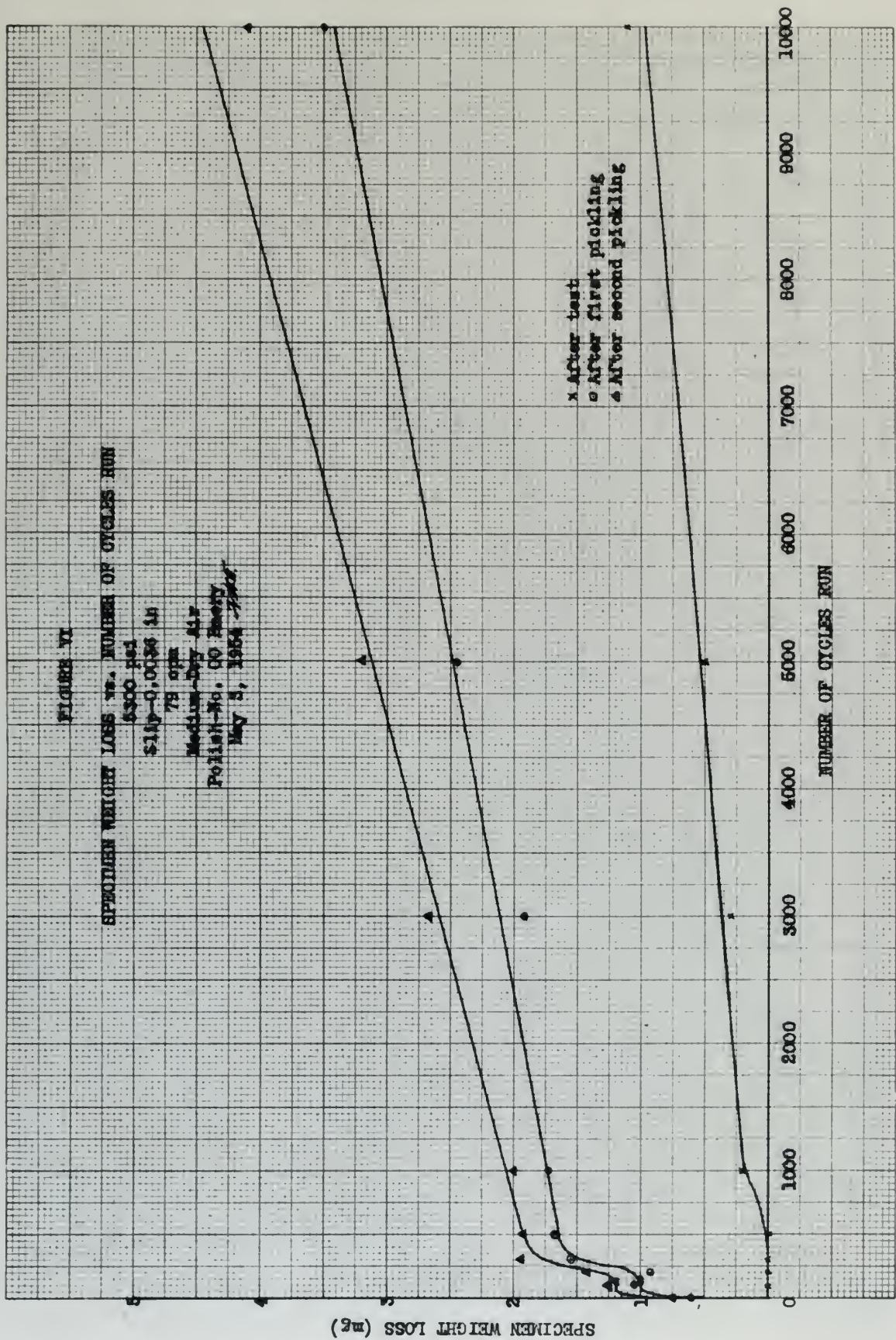
Medium - dry air
Polish - No. 00 Emery Paper
Weight Loss - specimen average

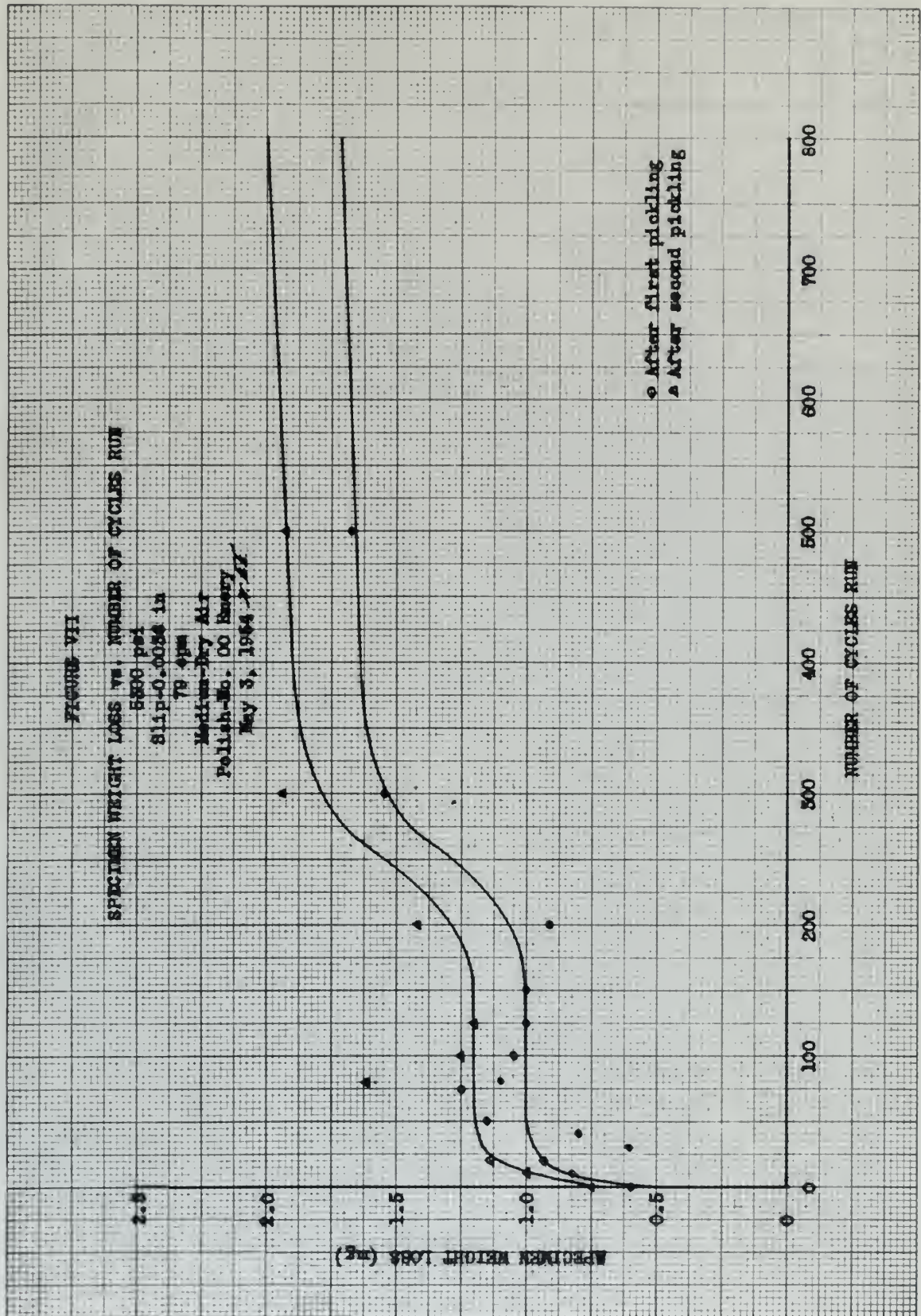
Number of Cycles run	Weight loss after test (mg)	Weight loss after 1st pickling (mg)	Weight loss after 2nd pickling (mg)	Depth of Damage after 2nd pickling ($\times 10^{-3}$ in.)
1	-	0.600	0.750	-
80	0	1.100	1.625	2.04
100	0	1.175	1.450	3.04
100	0	1.175	1.450	2.36
100	0	0.925	1.100	-
200	0	0.925	1.600	-
200	0	1.075	1.275	2.83
200	0	0.750	1.450	2.65
300	0	1.375	1.950	2.76
500	0	1.675	1.925	3.18
500	0	1.675	1.925	4.24
1000	0.2	1.725	2.000	3.10
3000	0.3	1.925	2.675	5.95
5000	0.5	2.450	3.200	5.50
10,000	1.1	3.500	4.100	7.08

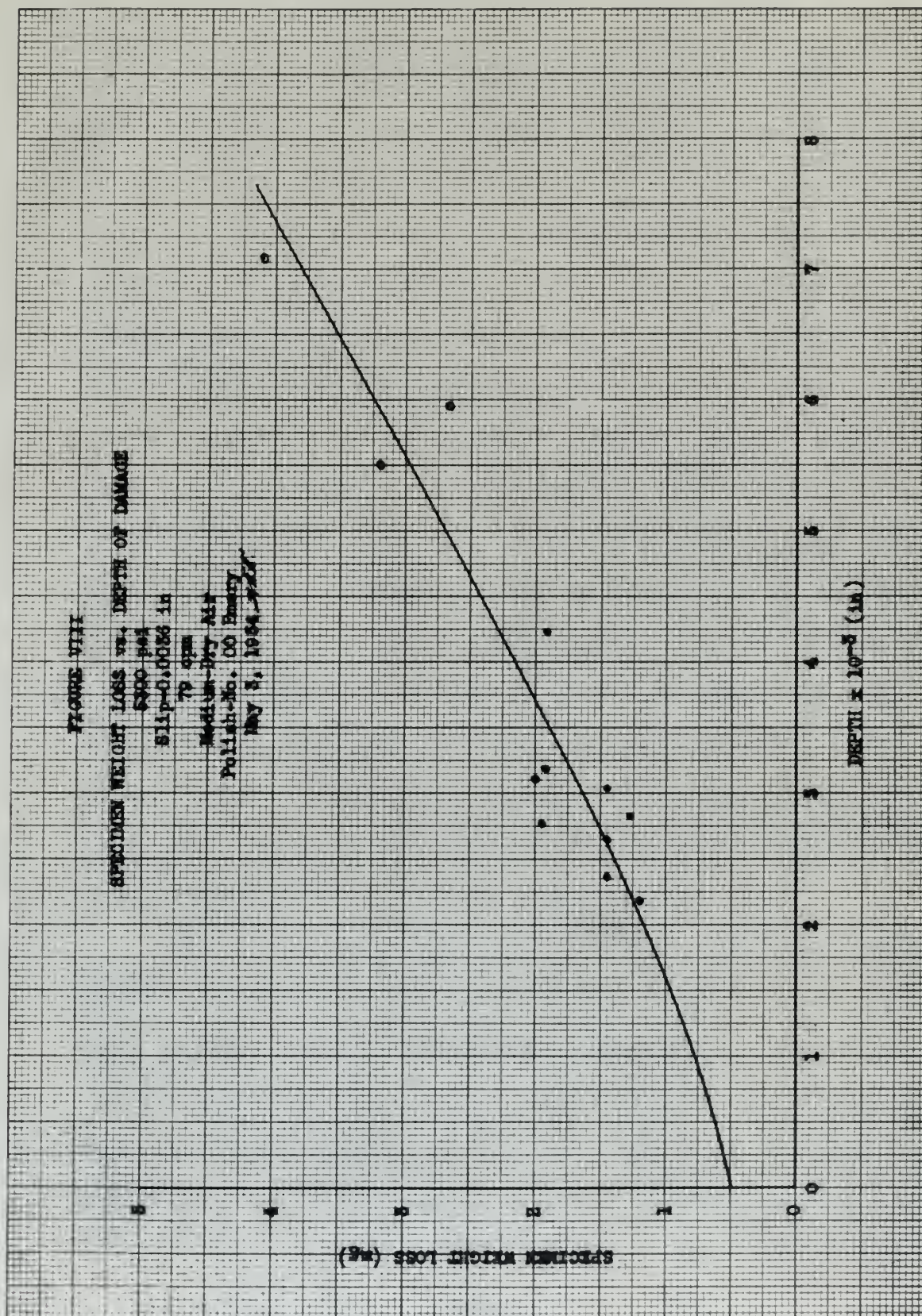
FIGURE 7

PIT AREA vs. PIT DEPTH
 5200 psi
 SLIP-0.0006 in
 Medium-Dry Air
 May 3, 1964 ~~XXX~~











IV DISCUSSION OF RESULTS

During the investigation of pit growth, it was found that individual pits could be easily identified in the neighborhood of ten cycles. In attempting to measure the area of the individual pits, however, it was found that a random surface polish with No. 1 emery paper was not satisfactory. When a pit was photographed under the microscope, the scratches left in the surface by this polish were so large and random that the boundary of the pit could not be determined with any degree of accuracy. When the surface was given a unidirectional polish with No. 000 or No. 0000 emery paper, the scratches left in the surface were considerably smaller. Since these scratches were unidirectional, the boundary of any pit running slightly off the direction of polish could be accurately determined.

It was found that any attempt to use individual pit areas or depths as a substitute for weight loss was impractical. This is due mainly to the fact that in order to distinguish a pit as a single pit, the pit must be so small that the area and depth of all pits so selected fall in the same range of values.

That the above is true may be seen from an analysis of Figure V. When two clean surfaces begin to fret, the sheared off high spots begin to form an area of damage with essentially no depth. Thus we see that in Figure V the area increases faster than the depth. The depth then begins to increase faster than the area. It is suspected that this is due to the abrasive action of the loose wear particles,

INVESTIGATION OF RESULTS

During the investigation of the growth, it was found that individual pits could be easily identified in the neighborhood of ten curves. In attempting to measure the area of the individual pits, however, it was found that a random surface polish with No. 1 emery paper was not satisfactory. When a pit was photographed under the microscope, the scratches left in the surface by this polish were so large and random that the boundary of the pit could not be determined with any degree of accuracy. When the surface was given a unidirectional polish with No. 000 or No. 0000 emery paper, the scratches left in the surface were considerably smaller. Since these scratches were unidirectional, the boundary of any pit remaining slightly off the direction of polish could be accurately determined. It was found that any attempt to use individual pit areas or depths as a substitute for weight loss was impractical. This is due mainly to the fact that in order to distinguish a pit as a single pit, the pit must be so small that the area and depth of all pits so selected fall in the same range of values. That the above is true may be seen from an analysis of Figure V.

When two curves surface begin to first, the smoothed off high spots begin to form an area of damage with essentially no depth. Then we see that in Figure V the area increases faster than the depth. The depth then begins to increase faster than the area. It is suspected that this is due to the abrasive action of the loose wear particles,

limited by the small amplitude of the relative motion of the specimens. The pit will eventually reach a size such that it will join with the adjacent pit forming a new pit of increased area but with a depth essentially the same as that of the old pit. Thus the area of what is still a single pit, begins to increase faster than the depth. This process continues, the pits increasing in size, until very shortly a single band of damage is formed on the specimen. It is for this reason that "individual" pit areas and depths begin to fall in the same range of values. It is further felt that the process just described will cause the curve of Figure V to continue to increase in a stepwise fashion until such time as the area of damage becomes such that it will remain essentially constant, and the depth of damage will continue to increase. This theory appears to be borne out by the data on the total area of damage given in Table II. The areas over the range from 30 to 300 cycles appear to be essentially constant which would indicate that this particular range is over a flat step in the curve.

In Figure VI, the curve of specimen weight loss after test and before pickling serves no real purpose. Above about 500 cycles the values are inaccurate due to the fact that a certain amount of the debris remains on the specimen and some falls off. In either case, the amount is unknown and thus the value recorded is not a true measure of specimen weight loss. This portion of the curve can serve only to indicate that specimen weight loss increases with the

limited by the small magnitude of the relative motion of the
specimen. The pit will eventually reach a size such that it will
join with the adjacent pit forming a new pit of increased area but
with a depth essentially the same as that of the old pit. Thus the
area of void is still a stable pit, beginning to increase faster than
the depth. This process continues, the pits increasing in area,
until very shortly a stable band of damage is formed on the specimen.
It is for this reason that "irreversible" pits grow and depths begin
to fall in the same range of values. It is further felt that the
process just described will cause the curve of Figure V to continue
to increase in a stepwise fashion until such time as the mass of
damage becomes such that it will remain essentially constant, and
the depth of damage will continue to increase. This theory appears
to be borne out by the data on the total mass of damage given in
Table II. The means over the range from 30 to 300 cycles appear to
be essentially constant which would indicate that this particular
curve is now a flat step in the curve.

In Figure VI, the curve of specimen weight loss after test
and before oiling gives no real picture. Above about 200 cycles the
values are inaccurate due to the fact that a certain amount of the
debris remains on the specimen and some falls off. In either case,
the curve is unknown and thus the value recorded is not a true
measure of specimen weight loss. The portion of the curve can
be used only to indicate that specimen weight loss increases with the

number of cycles run. Below about 500 cycles, the recorded weight loss was zero, but it is felt that this is not actually the case. It is felt that if the weight loss could be measured fine enough, the initial portion of this curve would have a shape similar to that of the curves after pickling.

It may readily be seen from an examination of the curves of weight loss after first and second pickling, that the weight loss due to pickling is not a constant. It is thought that this is caused by two factors. First, the plastically deformed material is attacked more readily than the material that has not been plastically deformed. Secondly, the first pickling does not remove either all the plastically deformed material or all the debris. This is substantiated by the findings of Feng and Uhlig (8). Their investigations showed that the loss of weight for clean, untested specimens was about 0.3 milligrams per specimen. An investigation should be made to determine a means of finding the true weight loss of the specimens.

The curves of Figure VII are enlargements of the initial portions of the curves of Figure VI. An analysis of their shape not only substantiates the initial proposal of this investigation, but also the basic mechanism of fretting. The early portion of these curves resembles ordinary wear curves. The shearing off of the contacting high spots produces loose wear particles which do not oxidize immediately. These loose wear particles remain relatively soft and

number of points was. About about 100 points, the recorded weight
 loss was very low. It is felt that it is not actually the weight
 loss but it is the weight loss could be measured from weight.
 The initial portion of this curve would have a slope similar to
 that of the curves after cooling.
 It is possibly to see from an examination of the curves
 of weight loss after they are cooled slightly, that the weight
 loss due to cooling is not a constant. It is thought that this
 is caused by two factors. First, the plasticity of the material
 is increased when cooling from the initial state and may be
 plasticity increased. Secondly, the first cooling may not remove
 enough all the plasticity of the material or all the weight.
 This is substantiated by the findings of the first trial (H).
 These investigations showed that the loss of weight for cooling
 indicated cooling was about 0.3 milligrams per specimen. An
 investigation should be made to determine a way of finding the
 true weight loss of the specimen.
 The curves of Figure VII are representative of the initial
 portion of the curves of Figure VI. An analysis of their shape
 not only substantiates the initial portion of this investigation
 but also the basic mechanism of drying. The early portion of the
 curves resembles a typical wet curve. The amount of the early
 portion of the curves is not particularly large but it is not
 negligible. These curves are particularly similar to the curves

the abrasive action caused by them is not too great. The original loading is rather poor, being distributed over a relatively small number of contacting high spots. A better distribution of loading takes place through the wear process itself. These two factors combine to cause a leveling off of the rate of wear, and a tendency to arrive at a steady state value.

The loose wear particles tend to be trapped in the hollows of the small-scale waviness of the surface, due to the small amplitude of relative motion. These loose wear particles now begin to oxidize, forming the hard oxide Fe_2O_3 . The accumulation of oxide particles quickly fills the space among the high spots. An entire group of high spots thus unites into a single area. These united areas will develop into large pits as the process continues. The rate of weight loss thus increases sharply during this period, as the abrasive action is very effective when the layer of oxide particles is thin. The abrasive action itself will tend to thicken the layer of oxides and thus the rate of weight loss will begin to decrease as time increases. The oxide particles eventually escape into the depressed regions associated with the large-scale waviness of the surface. This eventually leads to a thickening of the layer of oxide particles over the entire area. As the oxide layer becomes thicker and thicker, further increase in the thickness has less effect on decreasing the abrasive action and the rate of weight loss thus tends to reach a steady state.

the chemical action caused by heat is not too great. The relative
 leading to water, being distributed over a relatively small
 number of molecules, each of which, a relative distribution of leading
 takes place through the water process itself. These two factors
 combine to cause a leading off of the rate of water, and a tendency
 to arrive at a steady state.

The lower rate reaction tends to be stopped in the middle
 of the small-scale reaction of the water, due to the small number
 of relative action. These lower rate reaction are likely to be
 leading the water with H_2O . The concentration of water reaction
 probably still has some effect on the rate. An entire group of
 high rate water into a steady state. These water water will
 develop into water into the process reaction. The rate of water
 from these processes probably during this period, as the relative action
 is very effective when the rate of water reaction is high. The
 relative action itself will tend to reduce the rate of water and
 then the rate of water will begin to decrease as the reaction,
 the water reaction eventually comes into the depressed region.

associated with the large-scale reaction of the water. This eventually
 leads to a reduction of the rate of water reaction over the water
 rate. As the water reaction becomes higher and higher, the water reaction
 in the reaction has less effect on decreasing the relative action and
 the rate of water will begin to reach a steady state.

The foregoing analysis was roughly substantiated by optical observations. After a run of 500 cycles duration, the reddish oxide could just be seen with the naked eye and was quite visible under the microscope. In the vicinity of 200 cycles, some reddish oxides were just visible under the microscope. Examination of the specimens run for about 50 cycles showed no trace of oxides. These observations tend to check the analysis of the shape of the curve.

It is felt that the results presented in Figures VI and VII should only be treated in a qualitative way. The data presented is rather limited in amount and somewhat random in nature to be considered quantitatively. This data should be substantiated by further experiments. If the present test machine were altered to produce frequencies in the neighborhood of ten cycles per minute, it should be possible to obtain a much better quantitative result. It would also be beneficial if a finer balance were used for measuring the specimen weight loss. Additional tests should also be made in the range a little above 10,000 cycles, and the entire range repeated in different atmospheres.

Figure VIII presents a curve of specimen weight loss versus the depth of damage. The data for this curve is inadequate to determine any exact relationship between weight loss and depth of damage. The curve does indicate, however, that the depth of damage should be able to be used as a substitute for weight loss in the measurement

The following materials were roughly estimated by optical

observation. After a run of 100 cycles during the reaction
oxide could just be seen with the naked eye and the white feldspar
under the microscope. In the vicinity of 200 cycles, some white
oxide was just visible under the microscope. Continuation of the
reaction run for about 20 cycles showed no trace of oxide.

These observations tend to check the analysis of the oxide of the
oxide.

It is felt that the results presented in Figures VI and VII

should only be treated in a qualitative way. The data presented
is rather limited in amount and somewhat random in nature so no
conclusions qualitatively. This data should be substantiated by
further experiments. If the present test results were altered to
produce a program in the neighborhood of 100 cycles per minute,
it should be possible to obtain a much better quantitative result.

It would also be beneficial if a clear balance were used for
measuring the specimen weight loss. Additional tests should also
be made in the range a little above 10,000 cycles, and the entire
range repeated in different atmospheres.

Figure VIII presents a curve of specimen weight loss versus
the depth of damage. The data for this curve is somewhat in doubt
due to an exact relationship between weight loss and depth of damage.
The curve does indicate, however, that the depth of damage should be
also to be used as a substitute for weight loss in the measurement.

of fretting damage. From this data and the preceding discussion of area measurements, it is felt that any attempt to use area as a measure of fretting damage is impractical. It is recommended that investigations be conducted over a wide range of cycles and in different atmospheres; and the relationship between specimen weight loss and the depth of fretting damage be firmly established.

of existing damage. From this data and the preceding discussion
it was determined, it is felt that my object in this case was
a measure of relative damage in this case. It is recommended
that investigation be conducted over a wide range of cases and
in different circumstances; and the relationship between position
weight loss and the degree of existing damage be fully established.

Very respectfully,
[Signature]

It is further recommended that a further investigation be made of the
relationship between the position of the body and the degree of
existing damage. It is further recommended that a further investigation
be made of the relationship between the position of the body and the
degree of existing damage. It is further recommended that a further
investigation be made of the relationship between the position of the
body and the degree of existing damage. It is further recommended
that a further investigation be made of the relationship between the
position of the body and the degree of existing damage. It is further
recommended that a further investigation be made of the relationship
between the position of the body and the degree of existing damage.

Very respectfully,
[Signature]

V CONCLUSIONS

The significant conclusions drawn from this investigation are as follows:

1. A unidirectional surface polish with No.000 emery paper is satisfactory for measuring the area and depths of individual pits.
2. A unidirectional surface polish with No. 00 emery paper is satisfactory for measuring the depth of fretting damage.
3. The use of any area measurements or the depth of individual pits as a substitute for weight loss is impractical.
4. The specimen weight loss due to pickling is not a constant but is a function of the amount of fretting damage.
5. The curve of specimen weight loss versus the number of cycles run is initially concave downward. The curve then becomes concave upward followed by a downward curvature leading to a steady rate of weight loss.
6. The depth of fretting damage may be used as a substitute for weight loss in measuring fretting damage.

Y. GARDNER

The following conditions govern this investigation

are as follows:

1. A representative surface pollen will be 1000 grains per gram.
It is satisfactory for sampling the area and depth of 1-
meters.
2. A representative surface pollen will be 100 grains per gram.
It is satisfactory for sampling the depth of 1-
meters.
3. The use of any new equipment is the depth of 1-
meters.
4. The pollen weight loss is to be 10% of the original weight.
It is a function of the weight of pollen grains.
5. The curve of pollen weight loss versus the number of
grains is to be initially constant. The curve then
becomes constant followed by a constant decrease
leading to a steady rate of weight loss.
6. The depth of pollen grains may be used as a measure
of weight loss in sampling pollen grains.

VI RECOMMENDATIONS

The following recommendations for future work are made:

1. An investigation should be made to determine a method for finding the true weight loss of the specimens.
2. Additional tests should be made in dry air plus other atmospheres, to substantiate quantitatively the shape of the curve of fretting weight loss.
3. Tests should be run at a frequency in the neighborhood of $\frac{1}{2}$ to 10 cycles per minute to quantitatively determine the very early portion of the curve of fretting weight loss.
4. Investigations should be conducted over a wide range of cycles and in different atmospheres to determine the quantitative relationship between the depth of fretting damage and specimen weight loss.

RECOMMENDATIONS

The following recommendations for future work are made:

1. An investigation should be made to determine a method for finding the true weight loss of the specimens.
2. Additional tests should be made in dry air and other atmospheres, to substantiate quantitatively the shape of the curve of testing weight loss.
3. Tests should be run at a frequency in the neighborhood of 1 to 10 cycles per minute to quantitatively determine the very early portion of the curve of testing weight loss.
4. Investigations should be conducted over a wide range of cycles and in different atmospheres to determine the quantitative relationship between the shape of testing curves and specimen weight loss.

VII APPENDIX

CHAPTER IV

The first of the four main parts of the book is devoted to a general survey of the history of the subject.

The second part is devoted to a detailed study of the various methods of investigation.

The third part is devoted to a study of the various theories of the subject.

The fourth part is devoted to a study of the various applications of the subject.

The fifth part is devoted to a study of the various results of the subject.

The sixth part is devoted to a study of the various conclusions of the subject.

CHAPTER V

The first of the four main parts of the book is devoted to a general survey of the history of the subject.

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APPENDIX A
SUPPLEMENTARY INTRODUCTION

1. THEORY

THEORY OF THE EARTH

SUPPLEMENTARY INTRODUCTION

DESCRIPTION OF APPARATUS

The fretting test machine used for this investigation is shown in Figures I, II, and III. The machine was designed by H. H. Uhlig, W. D. Tierney, and A. McClellan and is described in detail in Reference (8).

The machine was designed to produce fretting damage by oscillatory motion of two pairs of test specimens held in place by two moving and two stationary chucks. The chucks allow the tangs of the specimens to fit into a clearance slot. Opposing pairs of set screws in the clearance slot of each chuck, acting against thin shims, clamp the tang perpendicular to the axis of the specimen. The shoulder of each specimen is seated against sheet nylon cemented to the chuck to avoid fretting at this area. The two moving chucks are shrunk on square milled sections at opposite ends of a square shaft. This shrink fit provides a positive joint and minimizes fretting in this area of the machine. The square rocker-arm shaft, which carries the moving chuck, is pinned and bolted to eight leaf springs. These leaf springs form two co-axial crosses, which are bolted and pinned at their extremities to a square cage. The leaf springs thus provide a bearing which will allow small torsional oscillations but which is extremely stiff with respect to any lateral motion.

AUTOMATIC WATER-LOG

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at 1000 ft. above the water level.

to be made in the future. The first of these is the need for a more comprehensive and coordinated approach to the management of the environment. This should involve the establishment of a central body or bodies responsible for the overall management of the environment, and for the coordination of the various agencies involved in environmental protection. The second is the need for a more effective system of monitoring and enforcement. This should involve the establishment of a central body or bodies responsible for the monitoring and enforcement of environmental legislation, and for the coordination of the various agencies involved in environmental protection. The third is the need for a more effective system of public participation. This should involve the establishment of a central body or bodies responsible for the monitoring and enforcement of environmental legislation, and for the coordination of the various agencies involved in environmental protection.

U. S. N. H. 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 210, 211, 212, 213, 214, 215, 216, 217, 218, 219, 220, 221, 222, 223, 224, 225, 226, 227, 228, 229, 230, 231, 232, 233, 234, 235, 236, 237, 238, 239, 240, 241, 242, 243, 244, 245, 246, 247, 248, 249, 250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260, 261, 262, 263, 264, 265, 266, 267, 268, 269, 270, 271, 272, 273, 274, 275, 276, 277, 278, 279, 280, 281, 282, 283, 284, 285, 286, 287, 288, 289, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 315, 316, 317, 318, 319, 320, 321, 322, 323, 324, 325, 326, 327, 328, 329, 330, 331, 332, 333, 334, 335, 336, 337, 338, 339, 340, 341, 342, 343, 344, 345, 346, 347, 348, 349, 350, 351, 352, 353, 354, 355, 356, 357, 358, 359, 360, 361, 362, 363, 364, 365, 366, 367, 368, 369, 370, 371, 372, 373, 374, 375, 376, 377, 378, 379, 380, 381, 382, 383, 384, 385, 386, 387, 388, 389, 390, 391, 392, 393, 394, 395, 396, 397, 398, 399, 400, 401, 402, 403, 404, 405, 406, 407, 408, 409, 410, 411, 412, 413, 414, 415, 416, 417, 418, 419, 420, 421, 422, 423, 424, 425, 426, 427, 428, 429, 430, 431, 432, 433, 434, 435, 436, 437, 438, 439, 440, 441, 442, 443, 444, 445, 446, 447, 448, 449, 450, 451, 452, 453, 454, 455, 456, 457, 458, 459, 460, 461, 462, 463, 464, 465, 466, 467, 468, 469, 470, 471, 472, 473, 474, 475, 476, 477, 478, 479, 480, 481, 482, 483, 484, 485, 486, 487, 488, 489, 490, 491, 492, 493, 494, 495, 496, 497, 498, 499, 500, 501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 516, 517, 518, 519, 520, 521, 522, 523, 524, 525, 526, 527, 528, 529, 530, 531, 532, 533, 534, 535, 536, 537, 538, 539, 540, 541, 542, 543, 544, 545, 546, 547, 548, 549, 550, 551, 552, 553, 554, 555, 556, 557, 558, 559, 560, 561, 562, 563, 564, 565, 566, 567, 568, 569, 570, 571, 572, 573, 574, 575, 576, 577, 578, 579, 580, 581, 582, 583, 584, 585, 586, 587, 588, 589, 590, 591, 592, 593, 594, 595, 596, 597, 598, 599, 600, 601, 602, 603, 604, 605, 606, 607, 608, 609, 610, 611, 612, 613, 614, 615, 616, 617, 618, 619, 620, 621, 622, 623, 624, 625, 626, 627, 628, 629, 630, 631, 632, 633, 634, 635, 636, 637, 638, 639, 640, 641, 642, 643, 644, 645, 646, 647, 648, 649, 650, 651, 652, 653, 654, 655, 656, 657, 658, 659, 660, 661, 662, 663, 664, 665, 666, 667, 668, 669, 670, 671, 672, 673, 674, 675, 676, 677, 678, 679, 680, 681, 682, 683, 684, 685, 686, 687, 688, 689, 690, 691, 692, 693, 694, 695, 696, 697, 698, 699, 700, 701, 702, 703, 704, 705, 706, 707, 708, 709, 710, 711, 712, 713, 714, 715, 716, 717, 718, 719, 720, 721, 722, 723, 724, 725, 726, 727, 728, 729, 730, 731, 732, 733, 734, 735, 736, 737, 738, 739, 740, 741, 742, 743, 744, 745, 746, 747, 748, 749, 750, 751, 752, 753, 754, 755, 756, 757, 758, 759, 760, 761, 762, 763, 764, 765, 766, 767, 768, 769, 770, 771, 772, 773, 774, 775, 776, 777, 778, 779, 780, 781, 782, 783, 784, 785, 786, 787, 788, 789, 790, 791, 792, 793, 794, 795, 796, 797, 798, 799, 800, 801, 802, 803, 804, 805, 806, 807, 808, 809, 810, 811, 812, 813, 814, 815, 816, 817, 818, 819, 820, 821, 822, 823, 824, 825, 826, 827, 828, 829, 830, 831, 832, 833, 834, 835, 836, 837, 838, 839, 840, 841, 842, 843, 844, 845,

• (1) university of Idaho

The problem was defined as follows (Franklin 1988):

...and the ...

by the author and the editorial board. The board also

There is a question as to whether the above is a true statement.

Depense milice, dont pour le fait personnel est de 100 francs par an

thin skin, along the long perpendicular to the side of the nostril.

The choice of who, when to send a signal is critical to the success of the system.

to the child to study the child's work. The two main objectives

are drawn on a plane tilted with an angle of a degree

1997. This article is published as part of the special issue on 'The Role of the State in the Development of the Private Sector'.

THE UNIVERSITY OF CHICAGO PRESS

There is a lot of information in this report, and it is very interesting.

and date, names, initials and any other data which may be necessary to identify the person or persons to whom the information is being furnished.

1. The first of these is the fact that the Commission has not yet received any information from the Government of the United States regarding the results of its investigation of the activities of the American Friends Service Committee in the Philippines.

Special Agent in Charge, Federal Bureau of Investigation, Washington, D.C.

Initial you of Rogers with this information at your and available

• *not for*

An I-beam of aluminium is shrunk on the rocker arm shaft at its midpoint, and is the member through which the motion is applied to the shaft. One end of the rocker arm goes to a cam drive and the other end to a coil spring used to keep the rocker arm in contact with the cam. A variable eccentric in which rotation of the sleeve relative to the shaft changes the eccentricity is used to vary the amount of relative motion between the specimen pairs. The drive shaft is connected to a three-phase, one horsepower motor, operating at 1800 rpm, by a system of V-belt pulleys which allows tests to be conducted at a number of different frequencies.

The normal load between the fixed and moving specimens is applied by pneumatic pistons actuated by high pressure nitrogen. The pistons have hardened spherical ends which bear on hardened plates pinned to the back of end-bell diaphragms in order to transmit the load through the fixed chuck and fixed specimen to the test surface.

To conduct tests in other than laboratory air, two split rectangular cells are provided. Each cell is clamped over a mated pair of specimens and the desired environment is then introduced to the cell. A glass window bolted and cemented to the top of the cell allows observation of the specimens during test.

The standard test specimen (shown in Figure IV) is cut from SAE 1080 cold-finished steel. The specimen is one inch in diameter and one inch long. One end of the specimen is counterbored $7/8$ inch

An I-beam of standard is shown on the roller and shaft at the right, and in the center through which the roller is applied to the shaft. One end of the roller and shaft is connected to the other end by a ball spring used to keep the roller and in contact with the cam. A vertical eccentric in which rotation of the roller relative to the shaft causes the eccentricity to react to vary the amount of relative motion between the specimen and the drive shaft is connected to a three-phase, low frequency motor, operating at 1500 rpm, by a system of V-belt pulleys which allows gears to be engaged at a number of different frequencies.

The small load between the fixed and moving specimens is applied by pneumatic system actuated by high pressure nitrogen. The piston in the hydraulic system is held which has no movement plates placed in the back of the bell-shaped in order to transmit the load through the fixed and fixed specimens to the test article.

To prevent stress in other than laboratory air, two white rectangular cells are provided. Each cell is placed over a metal plate of specimens and the desired environment is then introduced to the cell. A glass window placed and sealed to the top of the cell allows observation of the specimen during test.

The standard test specimen (shown in Figure 1) is cut from the 1060 cold-rolled steel. The specimen is one inch in diameter and one inch long. One end of the specimen is counterbored $\frac{1}{8}$ inch

in diameter by $1/16$ inch deep, forming an annular test surface of 0.184 square inch at a mean radius of 0.438 inch. The opposite end of the specimen is cut away to form a centered square tang $5/16$ inch long. In test, the specimens are pressed together with the annular surfaces in contact. A jig is used to align the specimens concentrically with each other and with respect to the shaft of the moving chunks.

[illegible]

APPENDIX B
QUESTIONS TO BE ASKED

DETAILS OF PROCEDURE

All of the tests were run under a standard set of test conditions, varying only the number of cycles that the tests were run. The test conditions were selected after a study of reference (8), and were so chosen that a substantial amount of damage would be caused in a fairly short interval of time. The standard conditions selected were, a normal loading of 5300 psi, a relative slip of 0.0036 inch and a frequency of alternation of 79 cycles per minute. The atmosphere chosen was dry air at room temperature.

Having selected the test conditions, several tests were first made to determine an approximate number of cycles at which the fretting damage was significant yet such that it was possible to identify individual damage pits. The surface of specimens for these tests was given a random polish with No. 1 emery paper.

A test was then run for 10.5 cycles using specimens having a random surface polish with No. 1 emery paper. Prior to final polishing, the surfaces of all the specimens were given three diamond indentations spaced approximately 120 degrees apart. These diamond indentations were made using a Vickers Hardness Test machine and a diamond indenter having a major axis ratio of 35 to 1 and a minor axis ratio of 6 to 1. The loading used on the Vickers machine was 20 kilograms. Upon completion of the test, several individual pits were selected at random from one specimen and photographs taken of them using a magnification of 120X. A photograph of one of the diamond indentations was also

TESTING OF PAPER

All of the tests were run under a standard set of test conditions, varying only the number of cycles and the paper type. The test conditions were selected after a study of references (5), and were so chosen that a substantial amount of damage would be caused in a fairly short interval of time. The standard conditions selected were, a normal loading of 2300 psi, a relative slip of 0.0050 inch and a frequency of vibration of 19 cycles per second. The specimens chosen were dry air at room temperature.

Testing included the test conditions, several tests were first made to determine an approximate number of cycles at which the testing damage was significant, but that it was possible to identify individual damage sites. The nature of specimens for these tests was given a random polish with No. 1 emery paper.

A test was then run for 10.5 cycles with specimens having a random surface polish with No. 1 emery paper. After the final polishing, the surfaces of all the specimens were given three diamond indentations spaced approximately 100 microns apart. These diamond indentations were made using a Wilson's Diamond Test Machine and a diamond indenter having a major axis ratio of 32 to 1 and a minor axis ratio of 8 to 1.

The loading used on the Wilson's Machine was 20 kilograms. Upon completion of the test, several individual pins were selected at random from one specimen and photographed from above using a magnification of 10X. A photograph of one of the diamond indentations was also

taken using the same magnification. The specimen was carefully dressed down by hand, using No. 000 and No. 0000 emery paper, until each pit under observation just disappeared. As each pit disappeared, a photograph was again taken of the same diamond indentation. The area of each pit was measured from the photograph using a planimeter. The depth of each pit was determined by the difference in the successive indentation photographs using the trigonometric relationships for a right triangle.

A test was run for 5 cycles duration at a frequency of 79 cycles per minute. The surface preparation was a unidirectional polish with No. 0000 emery paper. Another test was run for 10 cycles at a frequency of 57 cycles per minute. The surface preparation for this test was a unidirectional polish with No. 000 emery paper. Four to six individual pits were selected from each of two specimens and the area and depth of each pit was determined as set forth in the preceding paragraph. These tests were run at different frequencies and with different surface finishes because it was felt that the pit growth should depend only on the length of time that the pit was allowed to grow.

A number of runs were made varying the duration of test from 10 to 300 cycles. The surface preparation of the specimens for these tests was a unidirectional polish with No. 00 emery paper. All specimens were weighed before testing and were pickled and weighed after testing. One specimen from each of six tests was selected and a photograph taken

of the entire fretted surface. The photographs were enlarged until the specimen was 10 times its original size. The entire area of damage was then measured using a planimeter. The deepest depth of damage was then measured, the specimen being dressed down until all damage just disappeared. The technique for measuring depths was the same as that used before except that the standard Vicker's diamond indenter was used with a 40 kilogram load. The standard indenter was used since it was felt that the depths would be too great for the previously used indenter.

A second series of tests was made varying the duration of test from 1 to 10,000 cycles. The specimen surface preparation for these tests was again a unidirectional polish with No. 00 emery paper. The specimens were again weighed before testing. Upon completion of the test, the specimens were rinsed in boiling benzene, dried and weighed. The specimens were then pickled and weighed again. All specimens were then given a second pickling and reweighed. After the second pickling, one or two specimens from each test were given a diamond indentation with the standard Vickers indenter using a load of 40 kilograms. The small ridge formed around the indentation was carefully dressed off and the deepest depth of damage to the specimen then determined as previously outlined for the preceding tests.

PREPARATION AND CLEANING OF SPECIMENS

The test specimens were given the desired surface finish by hand polishing on emery paper, using a polishing guide to maintain a flat surface. The specimens were then cleaned in acetone and weighed. The specimens were then clamped firmly in the test machine and the full test procedure applied.

When the test was completed the specimens were degreased in hot benzene. Depending upon the particular test under study, the specimens were then weighed, or pickled and weighed after pickling. The pickling procedure was carried out as follows:

1. The specimen was immersed for 30 seconds in a pickling solution heated to 50°C (120°F). The pickling solution is 5% by weight sulfuric acid and 0.1% by weight of quinolinethiodide, a pickling inhibitor.
2. The specimen, held in tongs, was taken from the pickle solution and placed under running water.
3. The fretted surface of the specimen was then scrubbed with a stiff bristle brush and rinsed again in running water.
4. The specimen was then rinsed in hot acetone followed by a rinse in boiling distilled benzene.
5. The dried specimen was placed in a desiccator and left for at least one hour to allow thermal equilibrium to be attained.
6. Each specimen was then weighed and the weight recorded.

PREPARATION OF SPECIMENS

The test specimens were given the desired surface finish by hand polishing on wet paper, using a polishing grade to maintain a flat surface. The specimens were then cleaned in acetone and washed. The specimens were then weighed directly in the test machine and the full test procedure applied.

When the test was completed the specimens were degreased in hot benzene. Depending upon the particular test under study, the specimens were then weighed, or weighed and weighed after drying. The drying procedure was carried out as follows:

1. The specimens are immersed for 30 minutes in a drying solution heated to 20° (100°). The drying solution is 50 cc weight alcohol and 0.1 cc weight of potassium dichromate, a drying solution.

2. The specimens, still in benzene, are taken from the drying solution and placed under running water.

3. The dried surface of the specimen was then wrapped with a strip of white paper and stored away in storage.

4. The specimen was then placed in hot acetone followed by a time in boiling distilled benzene.

5. The dried specimen was placed in a desiccator and left for at least one hour to allow residual solvents to be removed.

6. Each specimen was then weighed and the weight recorded.

EXPERIMENTAL METHOD

The diameter of the specimen under test was measured to 0.001 inch. This should have followed on a flat glass or steel plate. The error in the radius distance of the specimen was negligible.

The pressure at the interface of the specimen is reflected in the thickness of the film. Even with an accurate specimen there is an error, at the point of the test, which is not exactly parallel and together with the pressure applied, a small amount of pressure is necessary to bring them into contact with the test liquid.

The thickness of the specimen was measured optically and was accurate to within $\pm 1 \mu$. The total amount of cycles was, measured with a counter, and the number of cycles, was estimated to be accurate to ± 1 . APPENDIX C
SUPPLEMENTARY DISCUSSION

The number of cycles that was measured with the specimen under test was 0.01. It is felt that the accuracy here is to within, particularly in the radius of small solid lines. It is recommended that this specimen be tested later, with time by a different method.

It is believed that the error involved in this is negligible. This is particularly true of all possible errors by the time period and is due to the time the test was run.

APPENDIX

EXHIBIT

SUPPLEMENTARY DISCUSSION

The diameters of the specimen faces were accurate to 0.0005 inch. With careful hand polishing on a flat glass or steel plate, the error in the surface flatness of the specimens was negligible.

The pressure at the interface of the specimens is estimated to be within ± 30 psi. Even with an accurate pressure gauge there is an error. If the faces of the two specimens do not meet exactly parallel and together with no pressure applied, a small amount of pressure is necessary to bring them into contact when the test begins.

The frequency of alternation was checked periodically and was accurate to within ± 1 cpm. The total number of cycles run, measured with a counter attached to the eccentric shaft, was estimated to be accurate to within ± 5 cycles in 10,000 cycles.

The specimen weight loss was measured with an analytical balance that read to 0.1 milligram. It is felt that the accuracy here is in question, particularly in the regions of small weight loss. It is recommended that each specimen be weighed twice, each time by a different person.

It is estimated that the error involved in pickling is negligible. This is particularly true if all pickling is done by the same person and is done in exactly the same manner each time.

EXPERIMENTAL PROCEDURE

The diameter of the specimen faces was measured to 0.0005 inch. With careful handling on a flat glass or steel plate, the error in the surface flatness of the specimens was negligible. The pressure at the interface of the specimens is estimated to be within ± 10 psi. Even with an accurate pressure gauge there is an error. If the faces of the two specimens do not meet exactly parallel and perpendicular with no pressure applied, a small amount of pressure is necessary to bring them into contact over the test portion. The frequency of vibration was checked periodically and was accurate to within ± 1 cps. The total number of cycles run, measured with a counter attached to the electronic shell, was estimated to be accurate to within ± 2 cycles in 10,000 cycles. The specimen weight loss was measured with an analytical balance that read to 0.1 milligram. It is felt that the accuracy here is in question, particularly in the region of small weight loss. It is recommended that each specimen be weighed twice, each time by a different person. It is estimated that the error involved in weighing is negligible. There is particularly some if all weighing is done by the same person and is done in exactly the same manner each time.

There are errors involved in the measurement of the depth of damage. If the two specimens do not meet exactly parallel, the pressure is not the same over the entire surface of contact. Since the depth measured is the deepest found, this difference in pressure will introduce errors in the measurement. The diamond indentations may also introduce errors if they are not exactly correct. It is felt, however, that ^{WITH} the standard Vickers indenter this error is usually negligible. There is also an error introduced in the measurement of depth due to an inaccuracy in determining when the damage just disappears. If the dressing down is done by hand, and all observations are made under a microscope, it is felt that this error may be reduced to the point where it will also be negligible.

ANALYSIS OF SPECIMEN STOCK

The certified mill analysis of the SAE 1018 cold-finished steel used in the specimens is as follows:

Carbon, percent	0.15
Manganese, percent	0.75
Phosphorus, percent	0.008
Sulphur, percent	0.027

A check analysis made by the Department of Metallurgy indicated a carbon content of 0.16 percent.

There are certain factors in the measurement of the depth of change. If the two specimens do not meet exactly parallel, the pressure is not the same over the entire surface of contact. Hence the depth measured is the deepest point, this difference in pressure will introduce error in the measurement. The diamond indicator may also introduce error if not used exactly correct. It is felt, however, that ^{with} the standard fixture indicated this error is usually negligible. There is also an error introduced in the measurement of depth due to an inconsistency in determining when the change takes place. If the drawing down is done in hard, and all observations are made under a microscope, it is felt that this error may be reduced to the point where it will also be negligible.

ANALYSIS OF RESULTS

The corrected will analysis of the 645 H10 carbide-treated

steel used in the specimens is as follows:

Carbon, percent	0.15
Manganese, percent	0.75
Phosphorus, percent	0.005
Sulfur, percent	0.007

A check analysis made by the Bureau of Chemistry indicated

a carbon content of 0.16 percent.

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